DESIGN AND EXPERIMENTAL STUDY OF AN INCLINED SPOON-DISC MAIZE SEED-METERING DEVICE
/
倾斜勺盘式玉米排种器的设计与试验研究

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ABSTRACT
To address the problems of multiple seeding, missed seeding, and insufficient operational stability commonly encountered during the operation of precision maize seed-metering devices, an inclined spoon-disc seed-metering device was designed in this study. The seed-metering process of maize kernels within the device was analysed, and the key components, including spoon wheel, partition plate, and seed-metering wheel, were structurally designed. Bench tests were conducted using a JPS-16 seed-metering device performance testing system. First, single-factor tests were performed to investigate the effects of metering-wheel rotational speed, overall inclination angle, and seed-layer height on the qualified index, multiple index, and miss index. Subsequently, a three-factor, five-level quadratic regression orthogonal rotational combination experiment was conducted using the metering-wheel rotational speed, overall inclination angle, and seed-layer height as the experimental factors. Optimization was performed with the objective of maximizing the qualified index. The optimal parameter combination was determined to be a seed-metering wheel rotational speed of 25 r·min⁻¹, an overall inclination angle of 27°, and a seed-layer height of 71.9 mm. Under these conditions, the model-predicted qualified index was 96.5%. In the verification tests, the average qualified index was 95.0%, with a relative error of 1.5% compared with the predicted value. The results can provide a reference for the structural design and operating-parameter optimization of inclined spoon-disc precision maize seed-metering devices.

摘要
针对玉米精量排种器在作业过程中易出现重播、漏播及排种稳定性不足的问题，本文设计了一种倾斜勺盘式排种器。分析玉米籽粒在排种器内的工作过程，并对排种勺轮、隔板及导种轮等关键部件进行了结构设计。在JPS-16 排种器性能测试系统上开展台架试验。首先通过单因素试验分析排种轮转速、整体倾斜角和种层高度对合格率、重播率和漏播率的影响；在此基础上，以排种轮转速、整体倾斜角和种层高度为试验因素，开展三因素五水平二次回归正交旋转组合试验。以合格率最大为目标进行优化，得到较优参数组合为排种轮转速 25 r·min⁻¹、整体倾斜角 27°、种层高度 71.9 mm，模型预测合格率为 96.5%。验证试验中合格率平均值为 95.0%，与预测值的相对误差为 1.5%。研究结果可为倾斜勺盘式玉米精量排种器的结构设计和作业参数优化提供参考。

INTRODUCTION
Maize is one of the major grain crops in China and plays an important role in ensuring food security and maintaining stable agricultural production (*Chen et al., 2025*). With the continuous expansion of large-scale maize cultivation and the advancement of fully mechanized production, increasingly stringent requirements have been imposed on planting efficiency, consistency of plant spacing, and the quality of precision single-seed placement (*Baghooee et al., 2024*).

The quality of maize planting directly affects seedling emergence uniformity, crop population structure, and subsequent yield formation. As the core component of a precision planter, the seed-metering device largely determines planting performance. Therefore, improving the operational performance of the seed-metering device is of great significance for enhancing maize planting quality (*Ding et al., 2024*).

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Currently, precision maize seed-metering devices can be broadly classified into mechanical and pneumatic types. Pneumatic seed-metering devices use negative- or positive-pressure airflow to perform seed pickup, singulation, and seed release (*Bakirov et al., 2025*). They offer high metering accuracy and good adaptability to high-speed operation and have therefore been widely used in large precision planters. However, these devices generally require a fan, an air chamber, and a pneumatic circuit, and they impose stringent requirements on system airtightness and pressure stability (*Gao et al., 2023*). Consequently, the overall machine structure is relatively complex, and the manufacturing and maintenance costs are comparatively high. Common mechanical seed-metering devices include finger-pickup, cell-wheel, pocket-wheel, and spoon-disc types. Among them, spoon-disc seed-metering devices use seed spoons to directly scoop individual kernels from the seed mass, offering a straightforward seed-pickup mechanism, a compact structure, and good adaptability (*Li et al., 2024*).

The seed-metering performance of a spoon-wheel seed-metering device is jointly affected by several factors, including the spoon geometry, rotational speed of the metering wheel, installation inclination angle of the seed-metering device, seed-layer height, and physical properties of the seeds. When the rotational speed of the metering wheel is too low, the seed spoons remain in contact with the seed mass for a relatively long period and may carry multiple kernels simultaneously, thereby increasing the probability of multiple seeding (*Cortez et al., 2020*). By contrast, when the rotational speed is excessively high, the residence time of the seed spoons in the filling zone is shortened, making it difficult for kernels to enter the spoon cavities in time and remain stably retained, which can readily result in missed seeding. The inclination angle of the seed-metering device changes the gravitational components acting on the kernels and the accumulation state of the seed mass in the filling zone, thereby affecting the seed-filling and singulation processes. Seed-layer height directly influences the number of kernels near the seed spoons and the pressure exerted by the seed mass. An excessively low seed layer may lead to insufficient seed filling, whereas an excessively high seed layer may cause multiple-kernel filling and increase the difficulty of seed singulation (*Lin et al., 2026*). Therefore, analysis of a single factor alone cannot accurately reflect the actual operating state of the seed-metering device, and the interactions among these factors require further investigation (*Sun et al., 2025*).

Previous studies have optimized the cell dimensions, seed-spoon geometry, rotational speed of the metering disc, and installation angle of mechanical seed-metering devices through theoretical analysis, discrete element simulation, and bench testing, and satisfactory seed-metering performance has been achieved (*Koller et al., 2016*). However, some studies have focused primarily on individual structural parameters of the metering wheel or seed-pickup elements, while relatively limited attention has been paid to the continuity of kernel transfer from the seed spoons to the seed-metering wheel, as well as the seed-retaining and seed-release processes. In addition, interactions and mutual constraints may exist among the rotational speed of the metering wheel, overall inclination angle, and seed-layer height (*Wang et al., 2026*). Consequently, the optimum level of an individual factor may not correspond to the optimal parameter combination under the combined effects of multiple factors (*Yang et al., 2025*). It is therefore necessary to consider the entire seed-metering process, analyse the key operating parameters and their interactions, and establish a regression model capable of describing the variation in seed-metering performance (*Zhao et al., 2026*).

Based on the above considerations, an inclined spoon-disc precision maize seed-metering device was designed in this study. The device uses a spoon-type metering wheel to perform seed scooping and singulation. A partition plate is employed to achieve the directional transfer of kernels from the spoon cavities to the seed-metering wheel, while the seed-metering wheel and housing jointly complete the seed-retaining and seed-release processes. First, the key components, including spoon wheel, partition plate, and seed-metering wheel, were structurally designed, and the movement of maize kernels within the seed-metering device was analysed. Subsequently, single-factor tests were conducted using Zhengdan 958 maize kernels to investigate the effects of seed-metering wheel rotational speed, overall inclination angle, and seed-layer height. Finally, a three-factor, five-level quadratic regression orthogonal rotatable combination design was employed to analyse the effects of the individual factors and their interactions on the qualified index. The operating parameters were then optimized and verified through bench tests. This study aims to provide a theoretical and experimental basis for the structural improvement and operating-parameter selection of inclined spoon-disc seed-metering devices.

MATERIALS AND METHODS

Structure and Operating Principle of the Seed-Metering Device

The inclined spoon-disc seed-metering device mainly consists of front and rear seed-metering housings, a seed-metering shaft, a spoon wheel, a partition plate, a seed-metering wheel, a brush, two end covers, and bearings, as shown in Fig. 1. The front and rear seed-metering housings are assembled to form the enclosed working chamber and provide support and positioning for the internal components. The spoon wheel and seed-metering wheel are driven by the same power source through a mechanical transmission system. They rotate synchronously in the same counterclockwise direction at a transmission ratio of 1:1. A fixed phase relationship is maintained between the spoon cavities and the corresponding U-shaped grooves of the seed-metering wheel, ensuring accurate seed transfer at the designed angular position.

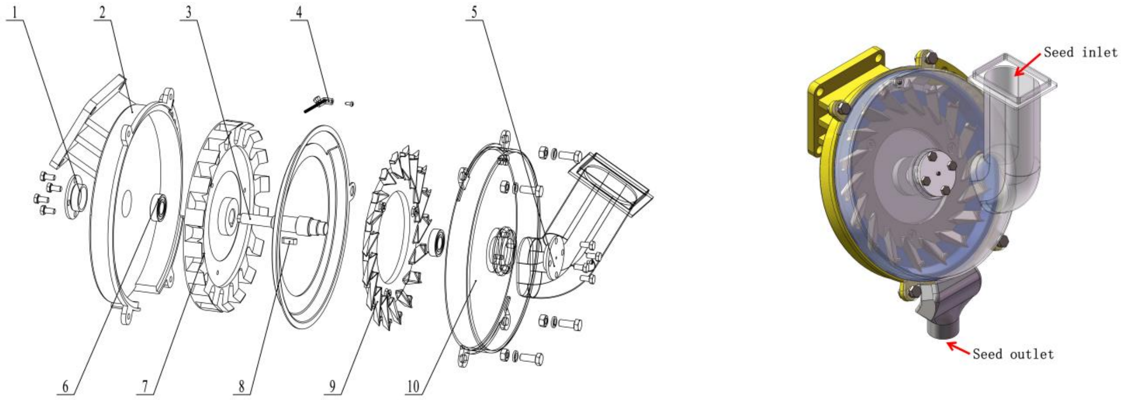

Fig. 1 - Structure of the inclined spoon-disc seed-metering device

1. Rear end cover; 2. Rear seed-metering housing; 3. Seed-metering shaft; 4. Brush; 5. Front end cover; 6. Deep-groove ball bearing; 7. seed-metering wheel; 8. Partition plate; 9. Spoon wheel; 10. Front seed-metering housing.

The movement of maize kernels within the seed-metering device consists of five successive stages: seed pickup, seed clearing, seed transfer, seed retention, and seed discharge, as shown in Fig. 2. During the seed-pickup stage, maize kernels enter the seed-filling zone at the bottom of the device and are captured by the spoon cavities. In the seed-clearing zone, excess kernels retained in unstable positions are removed under the combined effects of gravity, centrifugal force, and inter-kernel interactions, leaving one kernel in each spoon cavity. When the spoon reaches the seed-transfer zone, the retained kernel passes through the arc-shaped opening of the partition plate and enters the corresponding U-shaped groove of the seed-metering wheel.

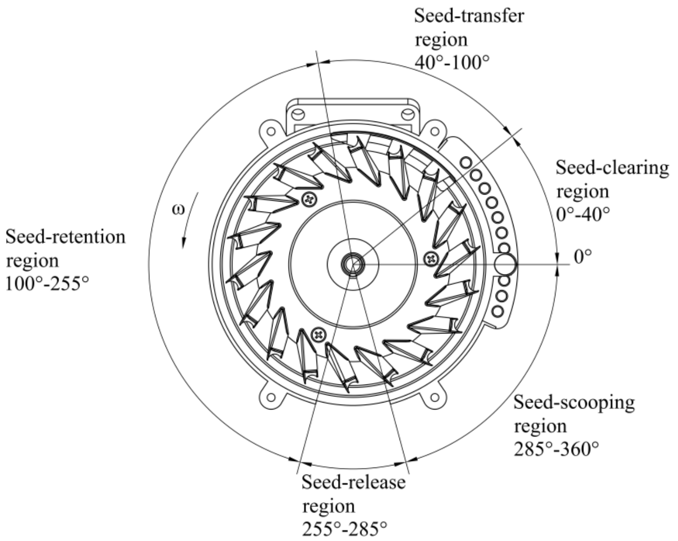

Fig. 2 - Operating process of the inclined spoon-disc seed-metering device

During the seed-retention stage, the kernel is constrained by the U-shaped groove and the seed-metering housing and is carried stably to the seed outlet. At the outlet, the structural constraint is removed, allowing the kernel to leave the groove under gravity and inertia and fall into the seed furrow. The proposed configuration reduces abnormal seed motion through the coordinated action of its components. The single-kernel spoon cavity and the seed-clearing process reduce multiple seed pickup.

The combined constraint of the U-shaped groove and the seed-metering housing prevents premature seed release. The dimensional matching among the spoon cavity, partition-plate opening, and U-shaped groove, together with an appropriate operating clearance, reduces kernel lodging and blockage. The arc-shaped transfer path and smooth structural transition reduce collision, squeezing, and seed damage. Moreover, the fixed 1:1 transmission ratio and phase relationship between the spoon wheel and seed-metering wheel ensure that each spoon cavity aligns with the corresponding U-shaped groove at the designed transfer position, thereby preventing delayed seed transfer.

Design of spoon wheel

Because the device developed in this study is primarily intended for precision single-seed maize planting, the structural configuration, principal dimensions, and kinematic characteristics of spoon wheel must be appropriately designed and analysed. A schematic diagram of the spoon cavity in the spoon wheel is shown in Fig. 3.

Fig. 3. Schematic diagram of the spoon cavity in spoon wheel

Based on the operating principle of the seed-metering device, maize-kernel length was selected as the characteristic dimension for determining the spoon-cavity size. Kernel length was defined as the maximum dimension along the longitudinal axis of an individual maize kernel. To ensure that maize kernels can enter the spoon cavity smoothly, the cavity diameter should be slightly larger than the mean kernel length. Therefore, the dimensional relationship between the spoon cavity and the maize kernel was expressed as:

$$2R=L+\delta \tag{1}$$

where L is the mean length of the Zhengdan 958 maize kernels, mm; R is the radius of the cylindrical spoon cavity, mm; and δ is the diametral design allowance, mm.

In this study, the mean length of the Zhengdan 958 maize kernels was 12.0 mm. Considering variations in kernel dimensions, changes in kernel orientation during entry into the spoon cavity, and manufacturing errors of the spoon cavity, the reasonable range of the design allowance was determined to be 0.5–1.5 mm. To balance seed-filling reliability and single-seed pickup performance, the intermediate value of δ=1.0 mm was selected. The corresponding spoon-cavity radius was R=6.5 mm. The selected allowance provides sufficient clearance for reliable kernel entry while preventing excessive enlargement of the spoon cavity. Combined with the removal of unstable excess kernels in the seed-clearing zone, the selected cavity size facilitates single-seed pickup and reduces the probability of multiple seed pickup.

The main design parameters of the spoon disc also include the number of seed spoons (Z_1), the pitch-circle radius of the spoon disc (r_1), and the outer radius of spoon wheel (r_2). Among these parameters, A schematic diagram of spoon wheel designed in this study is shown in Fig. 4. The angle (θ_2) is defined as the central angle between two adjacent seed spoons.

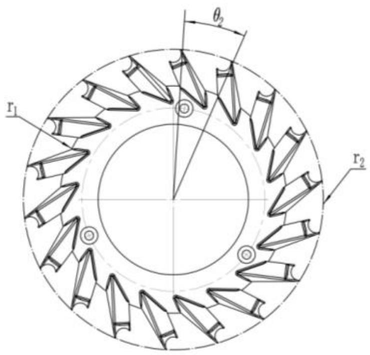

Fig. 4 - Structure of the spoon disc

According to Eq. (2), an increase in the number of seed spoons results in a decrease in the angular spacing between adjacent spoons. At a constant rotational speed of the seed-metering device, a greater number of kernels can therefore be discharged during each revolution of the spoon disc. When the required plant spacing remains unchanged, increasing the number of seed spoons can increase the operating speed of the planter while maintaining the same seeding rate.

$$Z_1 = \frac{360°}{\theta_2} \tag{2}$$

Based on the practical requirements of this study, the number of seed spoons was set to (Z_1=18). Accordingly, the pitch-circle radius of the spoon disc was determined as (r_1=83) mm, and the outer radius of spoon wheel was (r_2=115) mm. In addition, three M6 through-holes were uniformly arranged on the spoon disc at angular intervals of 120°, enabling spoon wheel to be securely connected to the seed-metering wheel.

Structural Design of the Partition Plate

The partition plate has an annular disc-shaped structure and is installed between the seed-metering housing and the cover. It is secured by a positioning structure and remains stationary during operation. A schematic diagram of the partition plate is shown in Fig. 5. A sector-shaped seed-transfer opening is arranged in the upper part of the partition plate. The starting position of the opening is located 15° forward of the vertical direction, and its opening angle is set to 65°; therefore, the seed-transfer angle of the partition plate is θ_3 = 65°. When the partition plate is adjusted to its highest position, the starting point of the seed-transfer zone is located at the arc-shaped opening. The angle between the horizontal direction and the line connecting this point to the centre of the partition plate is defined as θ_4, while the endpoint of the seed-transfer zone is located at the terminal end of the arc-shaped groove.

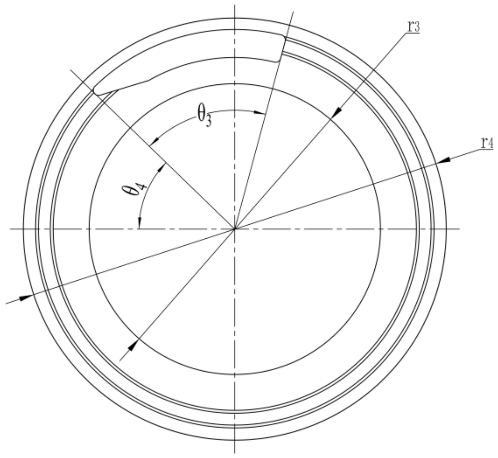

Fig. 5 - Structural schematic of the partition plate

Two positioning grooves are arranged along the lower outer edge of the partition plate. During assembly, the grooves are fitted into the seed-discharge opening at the lower part of the seed-metering device housing to restrict the rotation of the partition plate and prevent positional misalignment. Because the partition plate operates in coordination with the seed-metering spoon wheel and the seed-metering wheel, its structural dimensions should be determined according to the dimensions of these two components. Therefore, the following geometric relationships exist among the three components:

$$r_1 = r_3 \tag{3}$$

$$r_4 = r_5 \tag{4}$$

where r_3 is the inner radius of the partition plate, mm; r_4 is the outer radius of the partition plate, mm; and r_5 is the radius of the seed-metering wheel, mm.

Structural Design of the Seed-Metering Wheel

The seed-metering wheel is generally mounted on the main shaft of the seed-metering device and rotates synchronously with the spoon wheel. To ensure that the working circumferences of the two components coincide at the seed-transfer position, their working radii were designed to be equal, as expressed in Eq. (5). The seed-metering wheel has a cylindrical body with several uniformly distributed U-shaped seed grooves around its circumference. The number of seed grooves is equal to the number of spoon cavities on the spoon wheel, enabling the kernels delivered by the spoon wheel to be received smoothly. The spoon wheel and the seed-metering wheel are axially separated by the partition plate, with an axial operating clearance of 0.5 mm. The manufacturing tolerance of both the spoon wheel and the seed-metering wheel was controlled within ±0.1 mm. A schematic diagram of the seed-metering wheel is shown in Fig. 6.

$$r_5 = r_2 = 115mm \quad (5)$$

$$\theta_5 = \frac{\theta_2}{2} = 10° \quad (6)$$

$$s_1 = d_1 \quad (7)$$

$$Z_2 = Z_1 = 18 \quad (8)$$

where (s_1) is the height of the seed-metering wheel, mm; (d_1) is the width of the seed outlet, mm; θ_5 is the angle of a single U-shaped groove, °; θ_2 is the angular spacing between two adjacent seed spoons on the spoon-type seed-metering wheel, °; and (Z_2) is the number of U-shaped seed grooves on the seed-metering wheel.

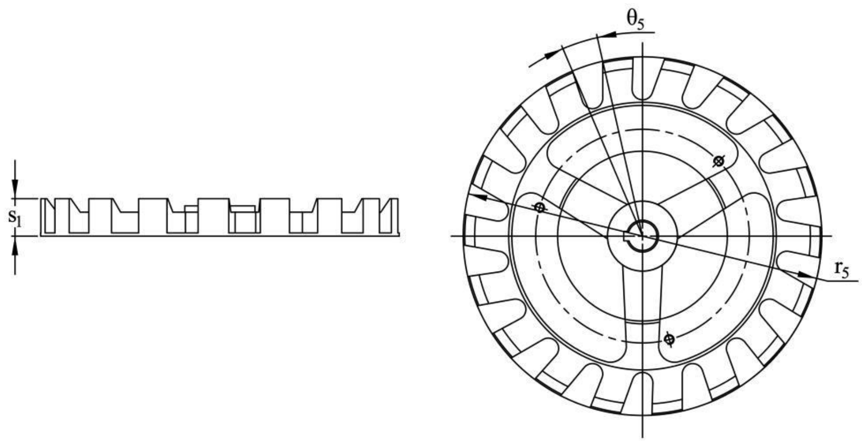

Fig. 6 - Schematic diagram of the seed-metering wheel

Bench Test

The bench tests were conducted using a JPS-16 seed-metering performance test system at the Key Laboratory of Intelligent Agricultural Machinery and Equipment, Heilongjiang Bayi Agricultural University. The system mainly consisted of a seed-metering-device mounting platform, a conveyor belt, an industrial camera, a control unit, an oil-applying and scraping device, and an illumination chamber. The conveyor belt was 0.9 m wide, and its speed was continuously adjustable from 0 to 16 km·h^{-1}. The seed-metering shaft speed ranged from 0 to 150 r·min^{-1}, with measurement and control accuracies of ±0.1% and ±0.5%, respectively. A computer-vision method was used to identify seed positions and calculate the spacing between adjacent seeds. The image-acquisition width was 400 mm, the acquisition frequency was 30–60 frames·s^{-1}, the seed-spacing resolution was 1 mm, and the mean measurement error was within ±2 mm. Before each test, the conveyor-belt speed, seed-metering shaft speed, and image-detection system were calibrated. The inclination angle was set and measured using the test system, with an accuracy of ±0.1°. The seed-layer height was measured using a steel ruler with 1-mm graduations, with an accuracy of ±1 mm. Data acquisition was initiated after the seed-metering device reached a stable operating state. Each test lasted 90 s, and 300 consecutive seed spacings were selected for statistical analysis. The tests were conducted at an ambient temperature of 20 ± 5 °C and a relative humidity of 40%–70%. Each treatment was repeated five times, and the mean value was used for subsequent analysis. Zhengdan 958 maize seeds were used in the experiments. The qualified index (A), multiple-seeding index (D), and miss-seeding index (M) were calculated using Eqs. (9)–(11), respectively (*Wang et al., 2026*).

$$A = \frac{n_1}{N} \times 100\% \quad (9)$$

$$D = \frac{n_2}{N} \times 100\% \quad (10)$$

$$M = \frac{n_3}{N} \times 100\% \quad (11)$$

Single-Factor Tests

To determine the effects of seed-metering wheel rotational speed, overall inclination angle, and seed-layer height on the performance of the inclined spoon-disc seed-metering device, three single-factor tests were conducted. The factor ranges were selected based on the operating range of the test system, preliminary tests, and the requirements of maize precision seeding. Maize kernels from the same cultivar, seed lot, and size grade were used throughout the tests. The treatment order within each single-factor test was randomized to reduce systematic errors. Except for the factor under investigation, all other operating and environmental conditions were kept constant. Each treatment was repeated five times, and 300 consecutive seed spacings were evaluated in each repetition. The arithmetic mean of the five repetitions was used as the final result. The qualified index, miss-seeding index, and multiple-seeding index were selected as the performance indicators, and the data were statistically analysed using IBM SPSS Statistics 26.0. To investigate the effect of seed-metering wheel rotational speed, the overall inclination angle and seed-layer height were maintained at 22.5° and 60 mm, respectively, while the rotational speed was set to 14, 17, 20, 23, 26, and 29 r·min^{-1}. To evaluate the effect of the overall inclination angle, the rotational speed and seed-layer height were maintained at 21 r·min^{-1} and 60 mm, respectively, while the inclination angle was set to 15°, 18°, 21°, 24°, 27°, and 30°. To examine the effect of seed-layer height, the rotational speed and overall inclination angle were maintained at 21 r·min^{-1} and 22.5°, respectively, while the seed-layer height was set to 40, 48, 56, 64, 72, and 80 mm.

Multi-Factor Test

Based on the single-factor test results, a three-factor, five-level central composite rotatable design was employed to investigate the individual and interaction effects of seed-metering wheel rotational speed, overall inclination angle, and seed-layer height on seed-metering performance. The qualified index, multiple-seeding index, and miss-seeding index were selected as the response variables. The experimental runs were conducted in a randomized order. Each run was repeated five times, and the response values were expressed as the mean ± standard deviation. The coded factor levels are presented in Table 1, and the experimental design and results are presented in Table 2.

Table 1

Coded levels of the experimental factors

Coded value	Factor		
	Seed-metering wheel rotational speed (r·min^{-1})	Overall inclination angle (°)	Seed-layer height (mm)
1.682	27.8	30	80
1	25	27	71.9
0	20.8	22.5	60
-1	16.7	18	48.1
-1.682	13.9	15	40

RESULTS AND DISCUSSIONS

Effect of Seed-Metering Wheel Rotational Speed on Seed-Metering Performance

Under an overall inclination angle of 22.5° and a seed-layer height of 60 mm, the effects of seed-metering wheel rotational speed on seed-metering performance are shown in Fig. 7. As the rotational speed of the seed-metering wheel increased from 14 to 23 r·min^{-1}, the qualified index increased from 85.1% to 96.3%, representing an increase of 11.2 percentage points. Meanwhile, the multiple-seeding index decreased from 9.6% to 1.6%, a reduction of 8.0 percentage points, and the miss-seeding index generally decreased from 4.1% to a relatively low level. When the rotational speed was further increased to 29 r·min^{-1}, the qualified index decreased to 87.4%, whereas the miss-seeding index increased markedly to 9.5%. In contrast, the multiple-seeding index increased only slightly to 2.3%. At a relatively low rotational speed, the seed spoons remained within the seed mass for a longer period, thereby increasing the likelihood of capturing multiple maize kernels simultaneously. Moreover, the relatively weak centrifugal effect acting on the kernels in the seed-clearing zone made it difficult for excess kernels located outside the spoon cavity to fall back into the seed mass in a timely manner, resulting in a relatively high multiple-seeding index. As the rotational speed increased, the disturbance exerted by the seed spoons on the seed mass became stronger. Consequently, excess kernels were more readily detached from the spoon cavities under the combined effects of gravity, centrifugal force, and inter-kernel collisions. This gradually reduced the multiple-seeding index and consequently increased the qualified index.

Table 2

The experimental design and results

Coded value	Factor			Qualified index y_1 (%)	multiple-seeding index y_2 (%)	miss-seeding index y_3 (%)
	Seed-metering wheel rotational speed (r·min⁻¹)	Overall inclination angle (°)	Seed-layer height (mm)			
1	25	27	71.9	96.6	4	2.2
2	25	27	48.1	94.2	2.2	4.3
3	25	18	71.9	94.2	2.4	5.8
4	25	18	48.1	92.6	0.4	7.9
5	16.7	27	71.9	93.9	4.3	3.7
6	16.7	27	48.1	91.3	2.9	6.5
7	16.7	18	71.9	93.2	2.6	4.3
8	16.7	18	48.1	93.9	1.9	4.6
9	27.8	22.5	60	93.7	1.6	6.1
10	13.9	22.5	60	91	2.5	6.6
11	20.8	30	60	94.4	3.4	2.6
12	20.8	15	60	93.6	2.7	4.1
13	20.8	22.5	80	92.9	3.9	3.2
14	20.8	22.5	40	92.1	2.2	6.1
15	20.8	22.5	60	95.3	2.4	1.5
16	20.8	22.5	60	93.6	1.7	1.6
17	20.8	22.5	60	95	1.2	3.4
18	20.8	22.5	60	95.2	2.1	2.3
19	20.8	22.5	60	95.1	2	3.6
20	20.8	22.5	60	94.2	1.4	3.8
21	20.8	22.5	60	94.8	2	3.7
22	20.8	22.5	60	94.9	2.7	1.5
23	20.8	22.5	60	95.3	1.2	4

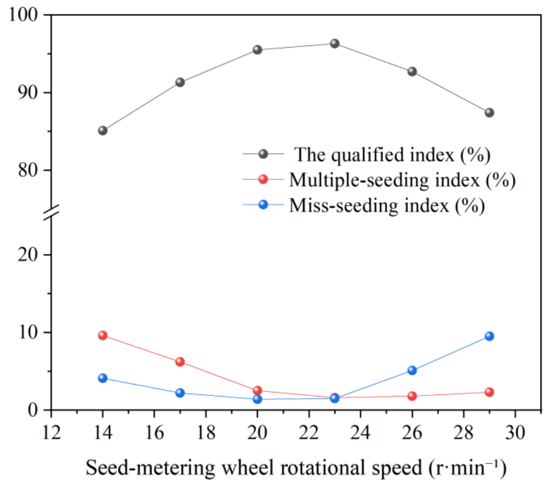

Fig. 7 - Effects of seed-metering wheel rotational speed on seed-metering performance

Effect of Overall Inclination Angle on Seed-Metering Performance

At a seed-metering wheel rotational speed of 21 r·min^{-1} and a seed-layer height of 60 mm, the effects of the overall inclination angle on seed-metering performance are shown in Fig. 8. As the overall inclination angle increased from 15° to 24°, the qualified index increased from 89.2% to 96.5%, corresponding to an increase of 7.3 percentage points. Meanwhile, the multiple-seeding index decreased from 3.1% to 1.7%, and the miss-seeding index decreased from 7.7% to 1.6%. When the inclination angle was further increased to 30°, the qualified index decreased to 91.7%, whereas the multiple-seeding index increased to 6.4% and the miss-seeding index increased slightly to 2.2%. At a relatively small overall inclination angle, the maize kernels were insufficiently concentrated in the seed-pickup zone under the action of gravity.

Consequently, the probability of effective contact between the seed spoons and the kernels was relatively low, making the spoon cavities more likely to remain unfilled and resulting in a higher miss-seeding index. As the inclination angle increased to an appropriate level, the component of gravitational force acting on the seed mass along the plane of the seed-metering disc increased. This promoted the movement of kernels toward the seed-pickup zone and improved the filling conditions of the seed spoons, thereby reducing the miss-seeding index and increasing the qualified index.

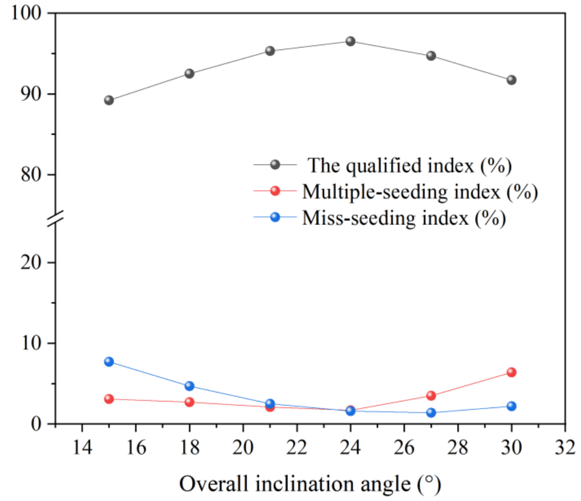

Fig. 8 - Effects of overall inclination angle on seed-metering performance

Effect of Seed-Layer Height on Seed-Metering Performance

At a seed-metering wheel rotational speed of 21 r·min^{-1} and an overall inclination angle of 22.5°, the effects of seed-layer height on seed-metering performance are shown in Fig. 9. As the seed-layer height increased from 40 to 64 mm, the qualified index increased from 88.6% to 96.4%, corresponding to an increase of 7.8 percentage points. Meanwhile, the miss-seeding index decreased from 9.2% to 0.9%, representing a reduction of 8.3 percentage points, whereas the multiple-seeding index increased only slightly from 2.1% to 2.6%. When the seed-layer height was further increased to 80 mm, the qualified index decreased to 90.5%, while the multiple-seeding index increased to 7.1% and the miss-seeding index increased to 2.3%. At a relatively low seed-layer height, fewer kernels were available for capture by the seed spoons within the seed-pickup zone. In addition, the contact pressure exerted by the seed mass on the seed spoons was insufficient, increasing the likelihood of unfilled spoon cavities and consequently resulting in a higher miss-seeding index. As the seed-layer height increased, both the number of kernels and the pressure exerted by the seed mass within the seed-pickup zone increased. This enhanced the probability of kernels entering the spoon cavities, thereby markedly reducing the miss-seeding index and gradually increasing the qualified index.

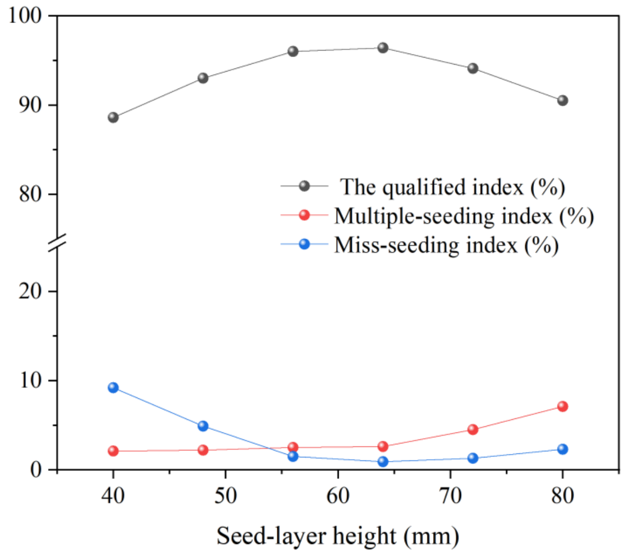

Fig. 9 - Effects of seed-layer height on seed-metering performance

Results and Analysis of the Central Composite Rotatable Design

The qualified index is an important indicator for evaluating the operating performance of the inclined spoon-disc seed-metering device. The analysis of variance for the regression model of the qualified index is presented in Table 3.

The model yielded an (F)-value of 6.88 with (*P*<0.01), indicating that the established quadratic regression model was highly significant. Significant regression relationships were observed between the qualified index and the rotational speed of the seed-metering wheel, the overall inclination angle, and the seed-layer height. The (*P*)-value for the lack-of-fit term was 0.1073, indicating that the lack of fit was not significant and that the model adequately described the relationships between the investigated factors and the qualified index. After eliminating the nonsignificant terms while retaining a significant overall model and a nonsignificant lack of fit, the regression equation for the qualified index in terms of coded variables was established as follows:

$$y_1 = 89.18 + 0.64x_1 - 1.11x_2 + -0.25x_3 + 0.03x_1x_2 + 0.005x_1x_3 + 0.009x_2x_3 - 0.04x_1^2 - 0.005x_2^2 - 0.004x_3^2 \quad (12)$$

where y_1 is the qualified index; x_1 is the coded value of the seed-metering wheel rotational speed; x_2 is the coded value of the overall inclination angle; and x_3 is the coded value of the seed-layer height.

Table 3

The results of the analysis of variance for the regression equations

Source of variance	Qualified index (%)			
	Square sum	Degrees of freedom	*F*	*P*
Model	32.74	9	6.88	0.0011**
x_1	7.12	1	13.47	0.0028**
x_2	0.89	1	1.69	0.2159
x_3	3.86	1	7.31	0.0181*
x_1x_2	4.35	1	8.23	0.0132*
x_1x_3	0.56	1	1.06	0.3214
x_2x_3	2.10	1	3.97	0.0676
x_1^2	7.55	1	14.28	0.0023**
x_2^2	0.16	1	0.30	0.5915
x_3^2	6.38	1	12.06	0.0041**
Residual	6.87	13		
Lost proposal	4.28	5	2.64	0.1073
Errors	2.60	8		
Sum of all	39.62	22		

Note: * indicates significant (P < 0.05) and ** indicates highly significant (P < 0.01).

Interaction Effect of Metering-Wheel Rotational Speed and Overall Inclination Angle

When the seed-layer height was fixed at 60 mm, the combined effects of seed-metering wheel rotational speed and overall inclination angle on the qualified index are shown in Fig. 10. As the rotational speed of the seed-metering wheel increased, the qualified index generally exhibited an initial increase followed by a subsequent decrease. Variations in the overall inclination angle resulted in markedly different changes in the qualified index at different rotational speeds. At relatively low rotational speeds, the seed spoons remained within the seed mass for a longer period, increasing the likelihood of simultaneously capturing multiple maize kernels and consequently increasing the multiple-seeding index. As the rotational speed increased further, the time available for the seed spoons to pass through the seed-pickup zone was shortened, making it difficult for the kernels to enter the spoon cavities completely and remain stably retained. This increased the probability of missed seeding and ultimately reduced the qualified index. The overall inclination angle altered the accumulation pattern and force direction of the maize kernels within the seed-pickup zone. At a relatively small inclination angle, the kernels were insufficiently concentrated toward the seed-pickup zone, resulting in a lower probability of effective contact between the kernels and the seed spoons. An appropriate increase in the inclination angle improved kernel accumulation and contact conditions, thereby facilitating seed filling.

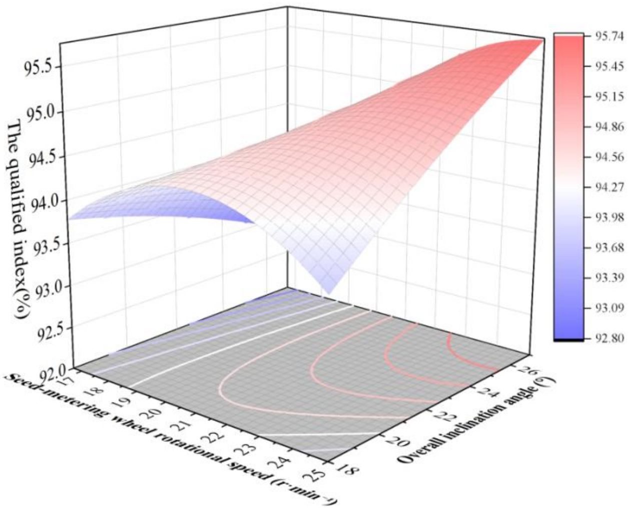

Fig. 10 - Effects of seed-metering wheel rotational speed and overall inclination angle on the qualified index

Interaction Effect of Seed-Metering Wheel Rotational Speed and Seed-Layer Height

When the overall inclination angle was fixed at 22.5°, the combined effects of seed-metering wheel rotational speed and seed-layer height on the qualified index are shown in Fig. 11. The response surface exhibited an arch-shaped profile, with a higher central region and lower peripheral regions, indicating that appropriate ranges existed for both the seed-metering wheel rotational speed and seed-layer height. As either the rotational speed or seed-layer height increased, the qualified index generally exhibited an initial increase followed by a decrease. At a relatively low seed-layer height, the number of kernels available for capture by the seed spoons in the seed-scooping region was limited. Moreover, the pressure exerted by the seed mass on the seed spoons was insufficient, increasing the likelihood of empty spoon cavities as the seed spoons passed through the seed mass and consequently increasing the miss-seeding index. An appropriate increase in seed-layer height enhanced the probability of contact between the kernels and seed spoons, improved the seed-filling conditions, and thereby increased the qualified index.

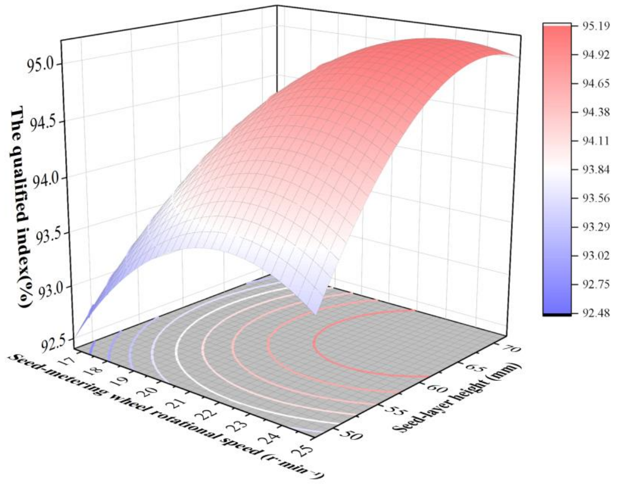

Fig. 11 - Effects of seed-metering wheel rotational speed and seed-layer height on the qualified index

Interaction Effect of Overall Inclination Angle and Seed-Layer Height

When the rotational speed of the seed-metering wheel was fixed at 20.85 r·min^{-1}, the combined effects of overall inclination angle and seed-layer height on the qualified index are shown in Fig. 12. The response surface exhibited more pronounced curvature along the seed-layer-height axis, whereas the variation along the overall-inclination-angle axis was relatively gradual. This indicated that seed-layer height had a greater effect on the qualified index than the overall inclination angle. As the seed-layer height increased, the qualified index initially increased and subsequently decreased. At a relatively low seed-layer height, an insufficient number of kernels were present around the seed spoons, increasing the likelihood of incomplete seed filling. As the seed-layer height increased, both the number of kernels and the pressure exerted by the seed mass in the seed-filling region increased, thereby enhancing the probability of kernel capture by the seed spoons.

However, with a further increase in seed-layer height, the probability of multiple kernels simultaneously entering a spoon cavity increased. Meanwhile, the intensified friction and compression among the kernels hindered the removal of surplus kernels, leading to an increase in the multiple-seeding index and a corresponding decrease in the qualified index.

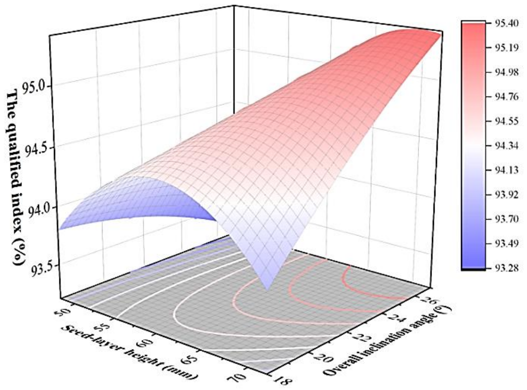

Fig. 12 - Effects of overall inclination angle and seed-layer height on the qualified index

To determine the optimal parameter combination, an optimization model was established within the factor ranges of the three-factor, five-level quadratic orthogonal rotatable design, with the qualified index maximized and the miss-seeding and multiple-seeding indices minimized as the optimization objectives, as shown in Eq.(13).

$$\begin{cases} \max y_1 \\ \min y_2 \\ \min\ y_3 \\ s.t. \begin{cases} 13.9 \le x_1 \le 27.8 \\ 15 \le x_2 \le 30 \\ 40 \le x_3 \le 80 \end{cases} \end{cases} \tag{13}$$

The numerical optimization module in Design-Expert software was used to solve the established regression model for the qualified index. Based on the fitting results obtained from the 23 experimental runs, the qualified index was set as the optimization objective to be maximized within the complete five-level ranges of the experimental factors. The theoretically optimal parameter combination was determined as follows: a seed-metering wheel rotational speed of 25 $r \cdot min^{-1}$, an overall inclination angle of 27°, and a seed-layer height of approximately 71.9 mm. Under these conditions, the qualified index predicted by the regression model was approximately 96.5%. Bench validation tests were subsequently conducted using the optimized parameter combination, as shown in Fig. 13.

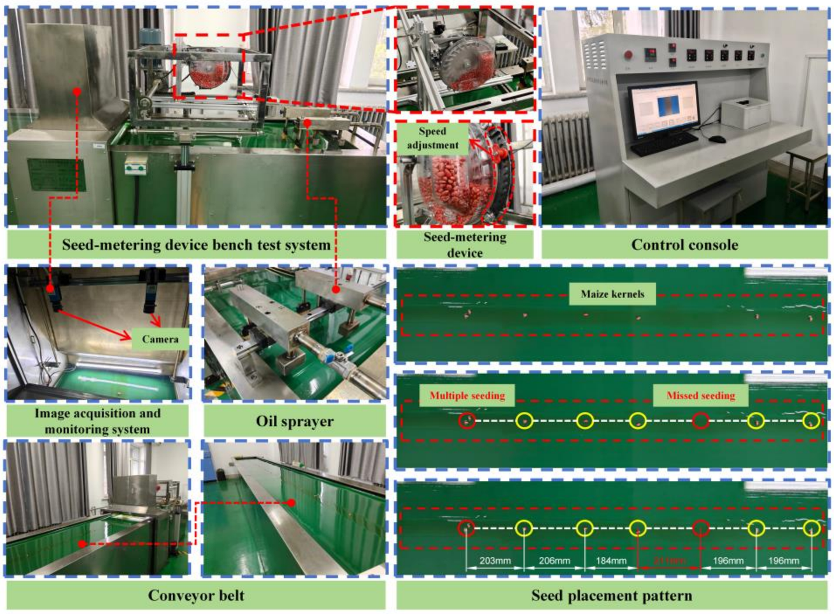

Fig. 13 - Results of the bench validation test under the optimized parameter combination

Three replicate tests were performed, and the mean qualified index was used as the validation result. The mean qualified index obtained experimentally was 95.0%, with a relative error of 1.5% compared with the model-predicted value. The experimental result was in good agreement with the predicted result, demonstrating that the established regression model had satisfactory predictive accuracy and that the optimized parameter combination was reasonable and reliable.

CONCLUSIONS

(1) An inclined spoon-disc seed-metering device was developed in this study. The spoon wheel and seed-metering wheel were driven synchronously at a transmission ratio of 1:1 and maintained a fixed phase relationship, ensuring that each spoon cavity was accurately aligned with the corresponding U-shaped groove at the designated seed-transfer position and thereby enabling precision maize seeding. In addition, the seed-metering wheel rotational speed, overall inclination angle, and seed-layer height exhibited pronounced nonlinear effects on seed-metering performance. Regression analysis showed that the rotational speed had the greatest effect on the qualified index, followed by the seed-layer height, whereas the main effect of the overall inclination angle was comparatively weak. A significant interaction was observed between the rotational speed and overall inclination angle, indicating that the appropriate inclination angle varied with rotational speed. These findings demonstrate that optimal seed-metering performance cannot be achieved by optimizing a single parameter independently; rather, the operating parameters must be properly coordinated.

(2) Multi-objective optimization identified the optimal parameter combination as a seed-metering wheel rotational speed of 25 $r \cdot min^{-1}$, an overall inclination angle of 27°, and a seed-layer height of 71.9 mm. Under these conditions, the qualified index predicted by the regression model was 96.5%, whereas the mean qualified index obtained from the validation tests was 95.0%, corresponding to a relative error of 1.5%. The close agreement between the predicted and experimental results indicates that the established regression model can reliably describe and optimize the seed-metering performance within the investigated ranges. Future studies will assess the adaptability of the device to different maize cultivars, conduct high-speed and field validation tests, and further evaluate its seed-metering performance under a broader range of operating conditions.

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